

A Taxonomy of reducing energy consumption methods in embedded system applications

Abstract

Power consumption and battery life are among the most important concerns in lightweight embedded systems. However, improving battery life performance has always been a major scientific challenge for researchers. Especially in the context of the Internet of Things (IoT). The Internet of Things, a sprawling network that connects smart devices and individuals, is profoundly impacting sectors as diverse as business, healthcare, social interactions, and politics. This complex platform includes sensors, local processors, wireless transmitters and central management stations, facilitating real-time data exchange across diverse domains. One of the critical hurdles faced by the Internet of Things is the inherent power limitations of small-sized devices. Extending the operational life of these devices is essential for optimal performance, which necessitates exploring different technologies and strategies to meet their power requirements. Many embedded systems are deployed, each presenting unique challenges and applications. Wearable devices, as a subset of the Internet of Things, present a particularly significant challenge due to their small size. The necessity of consolidation requires innovative power solutions to overcome the limitations, thus reducing the frequency of battery replacement or recharging. As the Internet of Things expands into smart cities, including healthcare environments, as well as remote patient monitoring distinct challenges emerge, underscoring the need for customized energy solutions. This research review focuses on various power minimization methods and technologies designed to meet the specific requirements of diverse IoT medical wearable devices within the ecosystem. The ultimate goal is to contribute to the realization of sustainable and efficient IoT power

ecosystems and address the challenges associated with energy consumption in embedded systems.

Introduction

The Internet of Things (IoT) has emerged as a transformative force, seamlessly interconnecting intelligent entities and individuals across diverse domains, spanning business, healthcare, social interactions, and political landscapes [1]. This intricate network, comprising sensors, local processors, wireless transmitters, and central management stations, facilitates real-time communication and data exchange on a vast scale. However, the realization of IoT's full potential encounters inherent challenges, particularly in the realm of power constraints, especially when considering small-scale devices [2]. The optimal performance of IoT devices relies heavily on extended operational periods, necessitating a critical exploration of innovative technologies to meet their power requirements [3]. Embedded systems play a pivotal role in addressing these challenges, as each application introduces unique obstacles and opportunities [4]. In the realm of healthcare, smart wearable devices, leveraging batteries for local vital signs processing and data transfer, offer users mobility and network connectivity advantages. However, the imperative for these devices to be compact imposes limitations on energy independence, often requiring frequent battery replacement or recharging [5], thereby presenting a challenge that demands creative energy solutions.

Conversely, devices like cameras or sensors in garages and transport vehicles require meticulous energy-saving considerations, each exhibiting distinct consumption characteristics. The birth of these diverse entities generates substantial data, leading to an urgent demand for efficient storage and processing solutions. In response, cloud computing emerges as a progressive technology poised to provide a remedy [6]. Another avenue involves employing specific communication protocols to regulate data transfer in proportion to energy consumption, with a diverse array of protocols to be explored [7]. Additionally, selecting the right controller contributes to reducing power consumption. Improving energy efficiency, particularly from an architectural perspective [8], the increasing popularity of lightweight embedded systems can be attributed to recent advancements in fabrication technology. these advancements have led to the development of more potent miniature processors, equipped with enhanced communication capabilities [9].

Moreover, technologies targeting high conversion and storage efficiency by harnessing energy from the environment, such as solar, kinetic, and wind energy, micro-vibrations, and varying temperatures, also play a crucial role in the evolving landscape of IoT power solutions [10]. Complementing these approaches, Power Gating techniques have emerged as a game-changer in mitigating power consumption within embedded systems. This strategic approach involves deactivating redundant or unused components of an embedded system, resulting in substantial reductions in power consumption, especially during dormant system states or inactive component phases [11] . The integration of such techniques marks a noteworthy stride towards optimizing power efficiency in IoT devices, thereby extending their operational lifespans while minimizing energy footprints. In tandem with device design, size becomes a determining factor—smaller devices with reduced components inherently consume less power.

This multifaceted exploration into power challenges and solutions within the IoT ecosystem aims to provide valuable insights that propel the field forward, fostering the development of resilient and energy-efficient technologies.

Literature review

furnishes a comprehensive survey encompassing the multifaceted challenges, technologies, and solutions pertinent to the pivotal theme of energy efficiency within wearable devices. Special attention is directed towards the healthcare domain and the diverse Internet of Things (IoT) scenarios where the effective management of energy resources holds paramount significance

the wearable sensor networks and their applications in healthcare, the main concern is the energy efficiency of on-body sensor networks. To address the challenge of energy efficiency in wearable sensor networks for HCR (human context recognition), proposed solutions include the use of specialized hardware platforms (such as PULP) and machine learning algorithms for real-time processing. Contributes to the broader goal of making these technologies more acceptable to patients by addressing the power issues associated with continuous monitoring in healthcare applications, Ensuring high accuracy in human context recognition remains a challenge, especially when aiming to reduce energy consumption.

Machine learning and artificial intelligence techniques can be combined to enhance the accuracy of context recognition, and use advanced patterns to improve efficiency The proposed integration of specialized hardware and intelligent algorithms represents a substantial stride towards achieving the overarching objective of making these technologies more acceptable to patients, thereby fostering their widespread adoption in continuous monitoring scenarios within healthcare applications [12] [13]. The energy

harvesting technologies in embedded systems and the development of autonomous devices in the context of the Internet of Things (IoT), and highlighted the importance of low-power wireless sensors for applications such as transportation, energy, healthcare, defense, and more. For sustainable operation of the systems, one of the major challenges highlighted was the necessity of flexibility in hardware design to meet a myriad of environments. Emphasizing the complex balance required to effectively meet this challenge. When proposing future solutions, the idea of adaptable hardware designs emerged as a pivotal suggestion. This includes creating devices that meet diverse environmental requirements, necessitating a shift towards adopting renewable energy technologies and wireless charging methodologies [14-18].

Addressing challenges and solutions related to energy efficiency, especially in the context of memory technologies in IoT devices and the importance of efficient memory solutions for IoT devices. Delves into the role of emerging memory technologies in enhancing the energy efficiency of IoT devices. This includes exploring memory solutions that reduce power consumption and extend battery life. The primary focus is on evaluating three types of memory options: flop-based, latch-based, and SRAM-based. The study reveals that latch-based memories show superior resource utilization, especially in terms of product power space, compared to SRAM-based and face-based memories. This evaluation provides insights into memory options that can significantly contribute to reducing overall system power and extending battery life for ultra-low-power IoT devices. However, it only focuses on memory options for ultra-low power IoT devices, specifically evaluating face-based, latch-based, and SRAM-based memories. As a solution, more comprehensive study could explore additional memory architectures and their trade-offs, taking into account factors such as scalability, reliability, and adaptability to diverse IoT applications [19] [20].

The Fog computing is introduced as a promising solution to the challenges posed by traditional cloud computing. It involves extending computing capabilities to the edge of the network, closer to the IoT devices. This helps in reducing latency, delay, and enhancing overall performance. The solution emphasizes the importance of real-time data processing, particularly in healthcare applications. Fog computing is positioned as a facilitator for real-time processing to improve performance. highlights the significance of fog computing in healthcare for real-time data processing, low latency, and energy efficiency. However, it could benefit from a more detailed exploration of the specific challenges unique to healthcare IoT applications, such as privacy concerns, security issues, and compliance with healthcare regulations [21][22]. The IoT applications in healthcare settings. It addresses specific challenges related to healthcare monitoring, patient tracking, and assisting individuals with specific medical conditions, specifically mention the use of Low Power Wide Area Network (LPWAN), LoRa (long range), technology for communications in IoT devices. But there is a lack of depth into how continuous tracking and monitoring impacts patients' behavior and well-being. Looking for psychological and emotional effects, as well as any potential resistance or discomfort experienced by patients, is essential for a comprehensive evaluation [23 - 25]. The IoT applications in battery monitoring and control, considerations of battery life and power exhaustion, validation through numerical examples or tests, attention to battery replacement strategies, and use of microcontrollers and communication modules for system functions. It proposes a mathematical framework (diffusion approximation) for modeling the process of power depletion in IoT batteries, taking into account factors such as active power consumption, sleep time, and battery capacity and also discusses monitoring the state of charge (SOC) of the battery and controlling the charging process remotely to address issues such as self-discharge and overcharging [26 - 28]. Applying IoT protocols, especially MQTT, COAP, HTTP in specialized environments. They both involve sensor integration and

address domain-specific challenges related to communication and battery management in IoT applications. As well as ensuring that energy-efficient protocols remain scalable as the number of connected devices increases.

It proposes that protocols be designed with scalability in mind, allowing for efficient communication in large-scale IoT deployments. Employing hierarchical or mesh network structures to distribute communications load [29] [30]. Develop innovative charging methods for wearable devices, integrate wireless power transfer technologies and consider the efficiency of the charging process. It explores the use of the human body as an element in the energy transfer process and addresses environmental and design criteria to improve performance. But it may not fully take into account various environmental factors, such as temperature, humidity and user activities, which can affect the performance of the technologies. Understanding the impact of environmental conditions is critical to the reliability and applicability of proposed solutions [31] [32].

The energy efficiency and task processing optimization for Internet of Things (IoT) devices, particularly in the context of mobile computing environments propose algorithms to optimize energy consumption and task processing. TEMS algorithm, which takes into account energy, time consumed during processing, data transfer cost, and energy in idle devices. As well as an algorithm that takes advantage of machine learning model predictions to reduce power consumption when using LPWA modems. The algorithm mainly focuses on e-health devices with different cellular signal conditions. Its applicability to a wider range of IoT devices and communication scenarios has not been widely discussed. As a future solution, extend the algorithm evaluation to different types of IoT devices and communication environments. Evaluate its performance in various scenarios to verify its universality and effectiveness [33][34].

Also using adaptive algorithms to address energy efficiency concerns. It presents the effects of a self-adaptation algorithm on the power

consumption of wearable physiological sensors. and the modified self-adaptive default algorithm (MSABA) to provide more accurate assessments of heart disease and algorithm for IoT devices based on multi-level hashing and the SHA family, called the Multi-Level Hashing Algorithm (MLHA) The MLHA is a promising new approach to hashing for IoT devices. The algorithm is efficient, secure, and energy-saving. It is also flexible and scalable, making it suitable for a wide range of IoT devices, from devices with limited resources to [35 - 37]. As summery, table (1) explore the short list of the literature.

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Author	year	Method	application	Findings
Victor Kartsch	2019	wearable sensing technologies, the PULP platform, HMI applications, hand gesture recognition, EMG sensors, real-time machine learning, and power efficiency considerations.	Healthcare applications	The integration of machine learning and artificial intelligence techniques is suggested to enhance context recognition accuracy and improve efficiency by identifying advanced patterns
Saeed Mohsen	2021	Energy Harvesting Technologies in Embedded Systems	Transportation. Energy. Healthcare. Defense. Other potential applications	survey of energy harvesting technologies in embedded systems and incorporation of renewable energy technologies and wireless charging methods to ensure sustainable and flexible operation of IoT systems..

Khader Mohammad	2019	Evaluation of memory techniques, main findings and practical implications	IoT applications	The evaluation of memory options provides insights into how different memory technologies can contribute to reducing the overall power consumption of IoT devices. This reduction in power consumption can, in turn, lead to extended battery life, which is crucial for ultra-low-power IoT devices
Ace Dimitrievski	2021	cloud computing and fog computing technologies	IoT and healthcare	the advantages of fog computing in healthcare applications, particularly in terms of reducing delay, optimizing energy usage, and providing real-time processing capabilities.
Christos Bouras	2021	LPWAN technology, specifically LoRa (Long Range), for long-distance connectivity in SAR applications	Search and Rescue Operations, Monitoring Vulnerable Populations, Military and Defense	that the introduced energy-efficient mechanism for LoRa networks, based on the user's state and wearable device battery levels, successfully reduces energy consumption in SAR operations without compromising the reliability of the

				network
P.T. Aikhoje	2023	The A6 GSM/GPRS module serves as the IoT platform, enabling remote monitoring and control through web browsing devices	Multi iot applications	successfully designs, constructs, and validates a remote battery monitoring and control device using IoT technology. The device addresses specific issues related to battery charging, and the successful implementation highlights the potential of IoT in creating practical and efficient solutions for power monitoring and control
M V Masdani	2018	technology includes the ESP8266 microcontroller board and the MQTT, CoAP, and HTTP protocols	broad applications across multiple IoT domains	The results show that CoAP has the lowest power consumption, and in contrast, MQTT has the highest power consumption. This shows that MQTT is not the protocol which consumes the least power.
NOOR MOHAMMED	2022	Wireless Power Transfer (WPT)	Wearable Technology, Office Environments, Healthcare and Medical Devices	suggests the potential for a new design paradigm that envisions completely charge-free wearable devices.
Julio C. S. dos Anjos	2021	TEMS algorithm	Smart Cities, Industrial IoT	development and effectiveness of a

			(IIoT), Healthcare, Wearable devices	dynamic cost model and the TEMS algorithm for task scheduling in IoT scenarios within mobile edge computing environments. The approach addresses the challenges of energy efficiency, task completion time, and cost optimization in a comprehensive manner, offering potential benefits for practical implementations in IoT systems.
Ahmad F. Subahi	2022	self-adaptive algorithm Self-Adaptive Bayesian Algorithm (MSABA)	Different health care settings	the Modified Self-Adaptive Bayesian Algorithm (MSABA) incorporated into the IoT platform for heart disease prediction shows superior performance compared to existing models

The Taxonomy of reducing energy consumption in embedded system methods:

There are several methods, one of these techniques is the "network longevity principle," which suggests achieving an energy-efficient and long-lasting IoT network by harmonizing design efforts between individual devices and the network. Designing IoT devices with a focus on energy efficiency is crucial for prolonging the overall. Low-power components, optimized algorithms, and intelligent power management strategies can

contribute to reducing energy consumption. Emphasizing collaboration, it calls for considering IoT device characteristics in sync with network requirements, aiming for a unified and sustainable design for enhanced efficiency in the IoT ecosystem [38].

Another methodology is to conserve battery life by optimizing data transmission. This can be achieved through techniques such as data compression or selective transmission of essential information. Additionally, adjusting parameters like Spreading Factor (SF), Coding Rate (CR), and Receiver Sensitivity (LoRa - RX dBm) can impact energy efficiency by tailoring communication range and data rate to specific operational needs [39].

Choosing and implementing low-power communications protocols such as MQTT (Message Queuing Telemetry Transport) is a lightweight, open-source messaging protocol designed for low-bandwidth, high-latency, or unreliable networks.

It follows a publish/subscribe model, allowing devices to communicate in a power-efficient manner by transmitting data only when needed.

The simplicity and efficiency of MQTT make it well-suited for IoT applications where minimizing power consumption is crucial. Or CoAP (Constrained Application Protocol) is designed specifically for constrained devices and networks, making it a suitable choice for IoT deployments with resource-constrained devices. It operates over UDP, which is lighter than TCP, and includes features such as multicast support, which reduces the power load of communications. These protocols are designed to achieve energy efficiency during data transmission between Internet of Things (IoT) devices [40][41]. Additionally, short-range communication technologies like Zigbee are a low-power, low-data-rate wireless communication standard designed for short-range communication in IoT applications.

It operates in the 2.4 GHz frequency band and supports mesh networking, allowing devices to relay data, extending the range without sacrificing

energy efficiency. or Bluetooth Low Energy (BLE) BLE is a power-efficient version of the classic Bluetooth protocol, specifically designed for low-power IoT devices. It is ideal for short-range communication and is widely used in applications like wearables, health monitoring devices, and smart home products.

BLE devices can operate in a low-power sleep mode and wake up quickly when data needs to be transmitted, thus conserving energy. can be utilized. Short-range communication technologies reduce the transmission distance and, thus, reduce power consumption while transferring data between devices [42].

Efficient data compression techniques can be implemented to reduce the amount of transferred data. Data compression techniques decrease the size of transmitted data, thereby reducing energy consumption during data transfer. By carefully selecting appropriate compression algorithms and considering the specific requirements of the IoT application, practitioners can strike a balance between data size reduction and computational overhead, ultimately enhancing the overall energy efficiency of the system [43 - 49].

Choosing energy-efficient sensors with low standby power and implementing on-device data processing can reduce the amount of data that needs to be transferred and processed in the cloud Selecting sensors with low standby power is crucial for minimizing the energy consumption during periods when the sensor is not actively collecting data. Standby power refers to the power consumed when the sensor is in a dormant state. the combination of selecting energy-efficient sensors and implementing on-device data processing represents a holistic approach to optimizing energy consumption in IoT applications. This methodology not only contributes to energy efficiency but also enhances the overall performance and cost-effectiveness of IoT systems. [50 - 54].

Implementing low-power modes such as sleep, idle, and standby modes, sleep mode Sleep mode involves putting the processor or specific components of the embedded system into a low-power state where most activities are temporarily halted, Idle mode is less aggressive than sleep mode and is typically used when the system is waiting for an event to occur, Standby mode is an even lower-power state compared to sleep or idle mode, often involving shutting down power to most components except for essential circuitry needed to maintain the system's state. implementing low-power modes is a fundamental technique in embedded systems design to achieve energy efficiency and conserve power during periods of inactivity [55] [56].

Dynamic Voltage and Frequency Scaling is a key strategy for optimizing power efficiency in modern computing systems. By dynamically adapting the processor's voltage and frequency to match the workload, DVFS enables devices to operate with maximum performance when needed and conserves power during periods of reduced demand, ultimately contributing to energy efficiency and extended battery life. [57] [58].

Power Gating and Clock Gating are techniques that prevent unnecessary power consumption. Power gating Power gating involves selectively shutting down power to specific blocks, components, or functional units within a chip when they are not in use. This is achieved by using switches or transistors to disconnect the power supply to the inactive portions., while clock gating Clock gating involves dynamically controlling the clock signal to specific sections of a circuit or functional units. When a particular section is idle, the clock signal to that section is gated or turned off. These techniques are pivotal techniques in power management for modern digital systems. Their implementation helps mitigate unnecessary power consumption during idle periods, contributing to energy-efficient designs, improved battery life in portable devices, and overall reduced environmental impact in electronic systems [59 - 66].

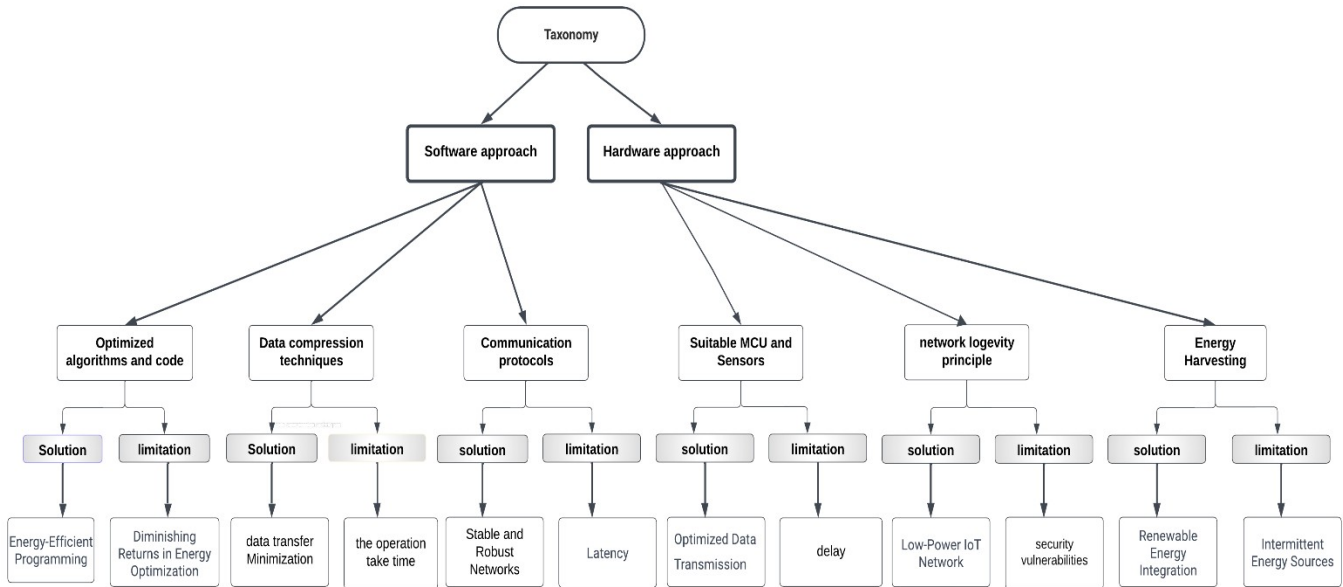
the implementation of energy harvesting techniques in IoT systems represents a sustainable and forward-thinking approach to address power challenges. By tapping into renewable energy sources like solar and kinetic energy, IoT devices can operate more autonomously, reducing their environmental impact and enhancing their overall reliability and longevity. [67 - 70]. Finally, table (2) summarized these methods for reducing energy consumption

Table (2) summarized methods for reducing energy consumption

Methodology	Propose solution	Limitation
network longevity principle	create a truly ultra-low-energy and long-lived IoT network	security vulnerabilities if not all devices adhere to the same standards
Choose energy-efficient sensors with low standby power	conserve battery life through optimizing data transmission involves a combination of techniques related to compression, selective transmission, and adjusting communication parameters	Compression and selective transmission may introduce delays, making this approach less suitable for applications with stringent real-time requirements
selection and implementation of low-power communication protocols.	Low-power communication protocols and short-range technologies help extend the battery life of IoT devices. Stable and Robust Networks	While these protocols aim to minimize power consumption during idle periods, the energy efficiency may decrease when devices are actively communicating
data compression techniques	reduce the amount of transferred data, leading to decreased energy	Compression and decompression algorithms require

	consumption during data transfer	computational resources, including CPU power and memory Compression and decompression operations take time, which may introduce latency into the communication process
Low-Power Modes	optimizing the operation of the embedded system to minimize power consumption when it is not actively performing tasks	The time it takes for a system to transition from a low-power state to an active state (wake-up time) can introduce unacceptable latency
Dynamic Voltage and Frequency Scaling (DVFS)	By dynamically adjusting performance based on the current workload, the device can operate more efficiently and conserve battery power during lighter tasks.	non-linear relationship between voltage, frequency, and power consumption. This non-linear relationship creates challenges in finding an optimal operating point that balances power efficiency with performance requirements.
Power Gating and Clock Gating	Both methods involve selectively disabling or reducing power to specific components or sections of a	When power gating or clock gating is applied, there is a latency associated with

	circuit when they are not actively in use	transitioning components from an idle state to an active state. This latency arises from the time it takes to power up or activate the components and synchronize them with the system
Energy Harvesting	Implementing energy harvesting techniques involves capturing and converting ambient energy from the environment, such as solar radiation or kinetic motion, into electrical power for use in electronic devices	Integrating energy harvesting into electronic devices adds design complexity. Efficient energy harvesting systems often require specialized power management circuits and control algorithms to optimize energy extraction, storage, and utilization. The availability of ambient energy sources, such as sunlight or motion, is often intermittent and unpredictable. This can result in periods of insufficient power



Summary

Through a comprehensive analysis of previous reviews, specific sections, and applied methodologies, various approaches have been explored in both hardware and software domains. The focus has been on mitigating energy consumption by strategically reducing processing operations within embedded systems. The findings reveal significant insights into the limitations of current systems and propose applicable solutions.

The culmination of this research not only establishes a foundation for understanding the intricacies of energy efficiency but also serves as a valuable resource for researchers and practitioners in the field. The methods presented may lean towards a singular direction, emphasizing either hardware or software modifications, or may take a hybrid approach that combines elements from both domains.

Conclusion

low-power embedded systems play a crucial role, offering a myriad of advantages such as enhanced energy efficiency, prolonged battery life, and minimized environmental impact. This significance is particularly pronounced in diverse applications, including Internet of Things devices, wearable electronics, medical implants, and smart sensors.

This paper has presented a comprehensive exploration of various methods aimed at power reduction, with a specific focus on both hardware and software aspects. The ongoing emphasis on diminishing power consumption has spurred advancements in hardware design, the formulation of energy-

efficient algorithms, and the integration of cutting-edge power management technologies.

As we delve into the findings, a discernible trend emerges, indicating that employing methods centered around software yields more effective power reduction. This preference is attributed to the inherent advantages of being low-cost and easily simulated, thereby driving researchers to intensify their focus on software-oriented solutions.

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